

Discovery of a Large-Scale Abundance Gradient in the Cluster of Galaxies AWM7 with ASCA

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ABSTRACT

A large-scale gradient in the metal abundance has been detected with *ASCA* from an X-ray bright cluster of galaxies AWM7. The metal abundance shows a peak of 0.5 solar at the center and smoothly declines to $\lesssim 0.2$ solar at a radius of 500 kpc. The gas temperature is found to be constant at 3.8 keV. The radial distribution of iron can be fit with a β -model with $\beta \sim 0.8$ assuming the same core radius (115 kpc) as that of the intracluster medium. The metal distribution in AWM7 suggests that the gas injected from galaxies is not efficiently mixed in the cluster space and traces the distribution of galaxies.

Subject headings: galaxies:abundance — galaxies:clusters: individual (AWM7)
— intergalactic medium — X-rays:galaxies

1. Introduction

Measurement of metal distribution in the hot intracluster medium (ICM hereafter) is important in constraining the origin of metals, in estimating how much mixing of the ICM has occurred, and in knowing the precise amount of metals in the ICM. The near-by X-ray bright cluster AWM7 is a suitable object since its low temperature makes the equivalent width of iron emission line high. The redshift of the central cD galaxy NGC1129 is 0.0176 (Beers et al. 1984). X-ray emission from this cluster has been studied with *Einstein* (Kriss, Cioffi, & Canizares 1983), *Ginga* (Tsuru 1992), *ROSAT* (Neumann & Böhringer 1995), and recently with *ASCA* in the PV phase (Ohashi et al. 1994; Xu et al. 1997). The emission is described by a thermal model with $kT = 3.8$ keV, excluding the center where the *ROSAT* PSPC data indicate a low temperature component. The *ASCA* data show that metal abundance is a factor of ~ 1.5 high at the center ($r < 4'$, Xu et al. 1997). However, large-scale distributions of temperature and abundance have not been studied with sufficient sensitivity.

In this letter, we report on the results from multi-pointing observations of AWM7 with *ASCA* (Tanaka, Inoue, & Holt 1994). This is the first example where a significant variation of metal abundance is found over a scale of 500 kpc. An $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ is employed indicating 30.7 kpc for $1'$ at AWM7, and a number fraction of $\text{Fe}/\text{H} = 4.68 \times 10^{-5}$ (Anders & Grevesse 1989) is used for the definition of the 1 solar iron abundance.

2. Observations and results

ASCA observed AWM7 at 6 positions, 2 centered at (R.A., Dec.)_{J2000} = (2^h54^m59^s, 41°37^m40^s) and (2^h53^m24^s, 41°36^m34^s) on Aug. 7, 1993, during the PV-phase, and 4 pointings centered at (R.A., Dec.)_{J2000} = (2^h55^m59^s, 41°33^m34^s), (2^h52^m12^s, 41°33^m26^s),

($2^{\text{h}}54^{\text{m}}26^{\text{s}}$, $41^{\circ}58^{\text{m}}28^{\text{s}}$), and ($2^{\text{h}}54^{\text{m}}27^{\text{s}}$, $41^{\circ}23^{\text{m}}25^{\text{s}}$) on Feb. 10-11, 1994 during the AO-1 phase. Each observation was performed with exposure time of ~ 20 ksec.

Xu et al. (1997) utilized the central pointing observation to investigate the detailed properties of the central region of the cluster. In order to look into the hot gas properties in a much larger scale, we analyzed the whole mapping data from 6 pointings by *ASCA*. In this letter we concentrate on the data obtained with the GIS (Ohashi et al. 1996; Makishima et al. 1996) which covers a larger area than the SIS. After the nominal event selection, an average of 20 blank sky data with point sources masked has been subtracted as the background. The systematic error in the generated GIS background flux is estimated to be 4 % rms (Ikebe 1995; Ikebe et al. 1995).

X-ray surface brightness distribution of AWM7 in the 0.7–10 keV range measured with the GIS is clearly elongated along east-west direction as shown by Neumann and Böhringer (1995), but no subclusters or irregular patchiness is seen. The data are fitted with the following model. We first assume a β -model $S(r) = S_0 [1 + (r/a)^2]^{-3\beta+1/2}$ where r is the projected radius, S_0 is the central surface brightness, and a is the core radius, respectively. This profile is then modified into an ellipse by either expanding or shrinking by a factor of $\sqrt{0.8}$ in perpendicular directions so that the minor and major axis ratio becomes 0.8 as given by Neumann and Böhringer (1995). Fitting the GIS data with this model in the energy range 2–10 keV with a radius of 0 to $45'$ from the center, we obtain the parameter values $a = 3'.75_{-0'.38}^{+0'.78}$ and $\beta = 0.58_{-0.02}^{+0.03}$. The errors indicate the 90% statistical errors for single parameter. These values are slightly different from those obtained by Neumann & Böhringer 1995 ($a = 3'.32 \pm 0'.16$ and $\beta = 0.53 \pm 0.01$ with 3σ errors). This is probably due to the difference in the sensitive energy range and the field of view, or maybe due to the accuracy of position determination of *ASCA* (Gotthelf 1996). We will use the β -model parameters obtained with the GIS data for the subsequent analysis.

EDITOR: PLACE FIGURE 1 HERE.

Spectral analysis has been carried out on data which are spatially divided into concentric regions around the cluster center. Figure 1 shows the GIS pulse-height spectra for 5 annular regions. The strong Fe-K line in the central region confirms the previous results (Xu et al. 1997). Moreover, we can also see that the Fe-K line equivalent width drops drastically towards the outer regions beyond $r \sim 15'$. The result suggests a large scale abundance gradient in ~ 500 kpc order. However, we need to examine the stray-light and point-spread function (PSF) properties of the X-ray telescope on *ASCA* (XRT, Serlemitsos et al. 1995) in detail to ensure the result.

The spectrum obtained from each annular region is contaminated by the photons arriving from different sky regions, even from outside of the field of view. This is because the PSF of the XRT extends to more than $10'$ and the effect of stray-light is significant (Serlemitsos et al. 1995). In the case of AWM7, approximately 30% of photons accumulated in the $r = 10' - 15'$ region originates in the central bright region ($r < 10'$). To cope with this, we have carried out spectral fits by calculating approximate response functions which take into account the relative amount of the flux contamination between different regions. This is the way similar to the method applied to the *ASCA* data of the Coma cluster (Honda et al. 1996). In the process of response calculation, we assume a uniform energy spectrum with the surface brightness profile obtained by the GIS data. This response compensates the flux contamination effect and enables us to derive the true temperature and abundance if they are uniform over the entire cluster. Corrections will be made to the result if any deviation from the uniformity is observed.

EDITOR: PLACE FIGURE 2 HERE.

We fit each spectrum from the concentric annular regions with a single temperature

Raymond-Smith model (Raymond & Smith 1977) with absorption. Spectral parameters are listed in Table 1, and the temperature profile is shown in Figure 2. The temperature is constant at 3.8 keV out to $r = 40'$ with a fluctuation of only about 10%. The value is consistent with the previous *Ginga* results (Tsuru 1992). The central region is somewhat cooler than the outer region as shown by Xu et al. (1997) and Mushotzky et al. (1996), but not enough to contradict with the isothermal assumption made above when the response function is prepared. The amount of N_{H} is consistent with the past results (Xu et al. 1997; Neumann & Böhringer 1995). The gradient in the equivalent width of Fe-K line shown in Figure 1 will not affect the result on the temperature, since effects of the Fe-K line equivalent width on the temperature are negligibly small compared with those of the continuum. The variation due to the systematic error in background flux is estimated to be 10 % for derived temperature even for the outermost $25' - 40'$ region.

As indicated in Figure 1, the metal abundance is, on the other hand, inconsistent with the “uniform” assumption employed for the present response. The profile roughly agrees with that derived by Xu et al. (1997). We therefore need to further correct the equivalent width of the Fe-K line by evaluating the flux contamination for the line component. We estimate this effect with the ray-tracing simulation for the XRT (Tsusaka et al. 1995). The GIS best-fit β -model is employed for the intrinsic surface brightness distribution of the continuum. For an approximation, we only consider contamination from inner regions and ignore that from outer regions. Since Figure 1 indicates an abundance gradient from the center to outer regions, contamination at the Fe-K line energy would be more dominated by that from inner regions. For each ring, inner regions always contribute more than 70% of the total contaminating photons. The abundances in outer regions are lowered by this correction; in the $60' - 80'$ region, the abundance is reduced to about 60 % of the original value obtained by the spectral fit. Calibration uncertainty in the stray-light flux is approximately 20 % (Kunieda et al. 1995), giving a fractional error of typically about 5 %

in the resultant line or continuum flux.

EDITOR: PLACE TABLE 1 HERE.

EDITOR: PLACE FIGURE 3 HERE.

The radial profile of the metal abundance after the correction described above is shown in Table 1 and Figure 3. The abundance reaches 0.5 solar in the innermost 5' region, which confirms the previous *ASCA* results (Xu et al. 1997; Ohashi et al. 1994), while the abundance drops to half at $r \sim 15'$ or at 460 kpc. The result is highly significant since overall systematic error is less than 20 %.

Finally, to look into the azimuthal dependence of the hot gas parameters, we extracted spectra from 4 sectors with 90° step each in the azimuthal angles and the radius range of 5' – 15' or 15' – 40'. The inner ring shows no azimuthal variation of temperature and abundance at a 90% confidence level. In the outer ring the temperature shows a peak-to-peak variation of 1 keV around the mean of 3.8 keV with a 90% error of 0.3 keV or 0.4 keV, and the abundance has too large an error to assess an azimuthal variation. Therefore, at least the azimuthal variation of the ICM temperature is inferred to be less than 40%.

3. Discussion

The *ASCA* observations of AWM7 have shown a radial drop of the metal abundance over a scale of 500 kpc. The ICM temperature, on the other hand, is found to be constant at 3.8 keV. The radial scale of the abundance change is far larger than the size of the cD galaxy and larger than the PSF of the XRT with a half power radius of $\sim 3'$ (Serlemitsos

et al. 1995). So far, significant change of abundance in the central < 100 kpc in a cluster has been observed in Centaurus, Virgo clusters and AWM7 itself (Fukazawa et al. 1994; Matsumoto et al. 1996; Xu et al. 1997). However, this is the first detection of a significant metal segregation on the cluster scale of ~ 500 kpc.

In Figure 3, we plotted the expected abundance when the density distribution of metals follows the β -model with the same core radius as the gas. We find that $\beta \sim 0.8$ can approximate the observed abundance gradient. This value is naturally greater than that of the ICM, and close to that for galaxy distribution derived for general clusters (Bahcall & Lubin 1994). Therefore, in AWM7 the metals seem to be tracing the galaxies. Metzler & Evrard (1994) also suggested the existence of the abundance gradient caused by a steeper distribution of galaxies than the gas. If metals are indeed injected from galaxies (Arnaud et al. 1992; Tsuru 1992), this feature suggests that no strong mixing has occurred in the ICM since the period of metal injection.

Let us briefly estimate how much iron can diffuse out in the Hubble time after a point-like injection. We shall neglect the sedimentation of iron based on the previous study by Rephaeli (1978). Spitzer (1962) gives formula for diffusion constants of ions in a plasma. Since the mean deflection time of iron is estimated as

$$t_D = 8 \times 10^{12} \text{ sec} \times \left(\frac{n_p}{10^{-4} \text{ cm}^{-3}} \right)^{-1} = 2.5 \times 10^5 \text{ yr},$$

the diffusion constant in a 4 keV plasma with a density of 10^{-4} cm^{-3} becomes about 10^{26} cm^2 . This implies that iron can diffuse in the ICM only out to 10 kpc at the maximum in the Hubble time. It seems, therefore, natural that the metals stay where they are injected and trace the distribution of galaxies, unless there is no large-scale bulk motion in the ICM. The data also suggests that the mixing due to galaxy motion is inefficient (see also Okazaki et al. 1993).

Recent evidences of significant temperature variation in clusters of galaxies suggest

that these clusters have experienced mergers in the past several Gyrs (e.g. Honda et al. 1996). Such a dynamical interaction between clusters would cause large-scale mixing of the ICM as well as temperature variation, as suggested from numerical merger simulations (Ishizaka & Mineshige 1996). The observed uniformity of the ICM temperature and the large-scale gradient in the abundance, tracing the galaxy distribution, supports the view that this cluster has been at rest from the time of the metal injection.

No other clusters have been observed with enough sensitivity in their outer regions. Bright near-by objects such as A1060 (Tamura et al. 1996) and Centaurs cluster (Fukazawa et al. 1994) have been studied only within 350 kpc from the center with *ASCA*. Clusters located at $z = 0.03 - 0.06$ are covered in a single GIS field, but the data have typically an order of magnitude lower statistics than the present case due to the strong vignetting of the XRT. This leads us to suspect that the large-scale abundance gradient could be present in many other clusters. However, it is also possible that AWM7 is special because it has a very elongated morphology and probably has a high ratio of gas to stellar mass (Neumann and Böhringer 1995). Future systematic studies with *ASCA* in the outer regions of other near-by clusters would clarify whether the abundance gradient is common or not.

This large-scale gradient in the metal distribution would have caused an overestimation of the total mass of iron with the previous non-imaging observations or with spatially non-slicing analysis. The measured abundance for AWM7, such as 0.42 with *Ginga* (Tsuru 1992: renormalized with $\text{Fe}/\text{H}=4.68\times10^{-5}$) and 0.39 with *ASCA* excluding $r < 3'$ (Mushotzky et al. 1996), can be significantly affected by the gradient. If we approximate the metal density distribution by a β -model with $\beta = 0.8$, the total iron mass in the ICM within 1.2 Mpc from the center decreases by a factor of 2. An alternative model assuming a linear drop of abundance from the center to 500 kpc following a constant level gives 0.18 solar as the best-fit value with a 90% error of ± 0.07 solar for the $15' - 40'$ region. This

model gives 10 % increase of the iron mass to the β -model estimation. Tsuru (1992) shows that the total iron mass in the ICM is proportional to the total stellar mass and that the present supernova rate can account for only 10 % of metals even accumulating for the Hubble time. If the metal distribution in the ICM has a large-scale gradient as in AWM7 or a patchy nature in the extreme case, the iron mass problem may be somewhat relaxed. A fine resolution (better than an arcminute) imaging of the metal distribution in clusters is necessary to obtain the true amount of metals in the cluster space. Such a study would also reveal the injection process and its history by the spatial size of the metal distribution around galaxies or along the galaxy trajectories.

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REFERENCES

- Anders, E., & Grevesse, N. 1989, *Geochimica et Cosmochimica Acta*, 53, 197.
- Arnaud, M., Rothenflug, R., Boulade, O., Vigroux, L., & Vangioni-Flam, E. 1992, *A&A*, 254, 49
- Bahcall, N. A., & Lubin, L. M. 1994, *ApJ*, 426, 513
- Beers, T. C., Geller, M. J., Huchra J. P., Latham, D. W., & Davis R. J. 1984, *ApJ*, 283, 33
- Fukazawa, Y., Ohashi, T., Fabian, A. C., Canizares, C. R., Ikebe, Y., Makishima, K., Mushotzky, R. F., & Yamashita, K. 1994, *PASJ*, 46, L55
- Gotthelf, E. 1996, *ASCA News*, 4, 31
- Honda, H., et al. 1996, *ApJ*, 473, L71
- Ikebe, Y. 1995, PhD thesis, University of Tokyo (RIKEN IPCR, CR-87)
- Ikebe, Y., Ishisaki, Y., Kubo, H., Idesawa, E., Takahashi, T., Makishima, K., & the GIS team 1995, *ASCA News*, 3, 13
- Ishizaka, C., & Mineshige, S. 1996, *PASJ*, 48, L37
- Kriss, G. A., Cioffi, D. F., & Canizares, C. R. 1983, *ApJ*, 272, 439
- Kunieda, H., Furuzawa, A., Watanabe, M., & the XRT Team 1995, *ASCA News*, 3, 3
- Makishima, K., et al. 1996, *PASJ*, 48, 171
- Matsumoto, H., Koyama, K., Awaki, H., Tomida, H., Tsuru, T., Mushotzky, R., & Hatsukade, I. 1996, *PASJ*, 48, 201
- Metzler, C. A., & Evrard, A. E. 1994, *ApJ*, 437, 564

- Mushotzky R., Loewenstein, M., Arnaud, K. A., Tamura, T., Fukazawa, Y., Matsushita, K., Kikuchi, K., & Hatsukade, I. 1996, *ApJ*, 466, 686
- Neumann, D. M., & Böhringer, H. 1995, *A&A*, 301, 865
- Ohashi, T., Fukazawa, Y., Ikebe, Y., Ezawa, H., Tamura, T., & Makishima, K. 1994, in *New Horizon of X-ray Astronomy*, ed. F. Makino, & T. Ohashi (Tokyo: Universal Academy Press), 273
- Ohashi, T., et al. 1996, *PASJ*, 48, 157
- Okazaki, T., Chiba, M., Kumai, Y., & Fujimoto, M., 1993, *PASJ*, 45, 669
- Raymond, J. C., & Smith, B. W. 1977, *ApJS*, 35, 419
- Rephaeli, Y. 1978, *ApJ*, 225, 335
- Serlemitsos, P. J., et al. 1995, *PASJ*, 47, 105
- Spitzer, L. 1962, *Physics of Fully Ionized Gases*, (New York: John Wiley & Sons)
- Tamura, T., et al. 1996, *PASJ*, 48, 671
- Tanaka, Y., Inoue, H. & Holt, S.S. 1994, *PASJ*, 46, L37
- Tusru, T. 1992, Ph. D. Thesis, University of Tokyo (ISAS RN-528)
- Tsusaka, Y., et al. 1995. *App. Opt.*, 34, 22
- Xu, H., Ezawa, H., Fukazawa, Y., Kikuchi, K., Makishima, K., Ohashi, T., & Tamura, T. 1997, *PASJ*, 49, 9

Fig. 1.— Energy spectra obtained by the GIS from 5 concentric annular region in AWM7. The arrow in each spectrum indicates the Fe-K emission line, which shows a gradual decrease of the equivalent width with radius.

Fig. 2.— Hot gas temperature in AWM7 for concentric annular regions. Each spectrum is fitted with the response function assuming a uniform spectrum as described in the text. The error bars indicate 90 % statistical errors.

Fig. 3.— Radial profile of the metal abundance in AWM7. The plotted values are corrected for the effects of PSF and stray light as described in the text. The error bars are 90 % statistical errors. The curves indicate expected abundance profiles when mass densities of metals follow β -models modified into an ellipse having a minor to major axis ratio of 0.8, for 3 different values of β_{metal} with the same core radius with the gas. The observed abundance profile suggests that metal distribution follows $\beta_{\text{metal}} \sim 0.8$.

Radius	0 – 5'	5' – 10'	10' – 15'	15' – 20'	20' – 30'	25' – 40'
Temperature [keV]	3.63 ± 0.09	$3.67^{+0.12}_{-0.09}$	$3.83^{+0.15}_{-0.14}$	3.74 ± 0.21	$4.10^{+0.32}_{-0.30}$	$3.51^{+0.43}_{-0.37}$
Abundance [solar]	0.51 ± 0.05	0.38 ± 0.07	0.30 ± 0.11	$0.14(< 0.29)$	$0.17(< 0.34)$	$0.15(< 0.39)$
N_{H} [10^{20} cm^{-2}]	8.7 ± 1.7	$9.8^{+1.7}_{-1.8}$	8.3 ± 2.0	$8.9^{+3.2}_{-2.5}$	$8.0^{+3.5}_{-3.4}$	$7.2^{+6.0}_{-5.4}$

Table 1: Results from the spectral fit for concentric annular regions in AWM7. Response function is for an isothermal gas, which is a consistent assumption with the listed results. The abundances are corrected for the contamination due to PSF and stray-light as described in the text. The errors indicate 90% statistical errors for a single parameter.





